微生物学报
*Acta Microbiologica Sinica*
2024, 64(8): 2661–2670
http://journals.im.ac.cn/actamicrocn
DOI: 10.13343/j.cnki.wsxb.20240079

# 藻藻共培养产生物质研究进展

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王涵，徐静，刘季鑫，林宜萌．藻藻共培养产生物质研究进展[J]．微生物学报, 2024, 64(8): 2661-2670.

WANG Han, XU Jing, LIU Jixin, LIN Yimeng. Research progress in substances produced by microalgal co-culture[J]. Acta Microbiologica Sinica, 2024, 64(8): 2661-2670.

**摘 要：**微藻富含脂质、蛋白质、胞外多糖等物质，具备生产高价值副产物潜能。与微藻单培养相比，微藻共培养具备生长速度快、抵抗力强等优势，可有效提高微藻生物质、油脂产量。藻藻共培养生物质生产受环境、营养成分及外源物质胁迫等因素的影响，所产生物质可用于生物燃料的生产以及食品工业的加工利用。本文综述了微藻共培养体系的类型及产高价值副产物的相关研究，总结了藻藻共培养产生物质的影响因素及资源化应用潜能，并对藻藻共培养的前景与挑战进行了展望。

**关键词：**微藻；共培养；生物质；资源化应用

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资助项目：黑龙江省自然科学基金(LH2020C089)；国家自然科学基金(32071519)；黑龙江省高校基本科研业务费(2021-KYYWF-0014, 2022-KYYWF-1080)

This work was supported by the Natural Science Foundation of Heilongjiang Province (LH2020C089), the National Natural Science Foundation of China (32071519), and the Heilongjiang Province University Basic Research Foundation (2021-KYYWF-0014, 2022-KYYWF-1080).

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Received: 2024-01-31; Accepted: 2024-05-21; Published online: 2024-05-24

# Research progress in substances produced by microalgal co-culture

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**Abstract:** Microalgae are rich in lipids, proteins, and exopolysaccharides, serving as potential producers of high-value by-products. Compared with monoculture, microalgal co-culture offers advantages such as fast growth rates and strong resistance, increasing the microalgal biomass and lipid production. Biomass production by microalgae co-culture is influenced by environmental conditions, nutrient composition, and external stress, and the produced biomass can be utilized for biofuel production and food processing. This article introduces the types of microalgal co-culture systems and reviews the related studies on the production of high-value by-products. It summarizes the factors influencing biomass production in microalgal co-culture systems and highlights the potential of microalgal co-culture for resource utilization. Furthermore, this article discusses the prospects and challenges of microalgal co-culture.

**Keywords:** microalgae; co-culture; biomass; resource utilization

微藻因生长迅速、光合效率高、不占用耕地、产油率高，被称为可替代化石燃料的可再生资源[1]。当微藻进行纯培养时细胞生长以及脂质合成积累较低，易受其他细菌污染，相比之下，混合培养可以提高微藻的生物质生产，促进脂质的积累。在微藻共培养体系中，微藻间通过细胞接触而相互促进，使微藻所产生物质以及产油率大大增加[2-3]。本文以不同种藻类共培养为背景，介绍了微藻共培养系统类型、藻藻共培养体系中生物质和油脂产率的变化、藻藻共培养对生物质成分的影响以及共培养产生物质的影响因素，最后总结了藻藻共培养资源化应用，为后续研究提供参考。

## 1 微藻共培养系统类型

### 1.1 微藻与细菌共培养

微藻与细菌通过营养交换、信号转导以及基因转移，在共生培养时可以提高生物质和脂质生产率[4]。通过营养交换，微藻光合作用过程中所产生的有机物被细菌吸收利用，细菌所产代谢产物供微藻生长利用，有助于建立高效的微藻-细菌共培养体系。本课题组 Li 等曾建立单针藻(*Monoraphidium* sp.) HDMA-11 与链霉菌野尻链霉菌(*Streptomyces nojiriensis*)共培养体系，发现 *S. nojiriensis* 代谢物可促进 *Monoraphidium* sp. HDMA-11 的生长，在共培养体系中 *Monoraphidium* sp. HDMA-11 生物质和脂质产量分别提高了 525.8%和 155.1%[5]。

微藻与细菌之间通过信号转导机制相互作用，细菌分泌化学信号，这些信号诱导了藻类发生形态变化。微藻与细菌之间基因转移为基因的水平转移，研究表明甲藻质体基因组上存在拟杆菌进化支的噬冷菌属(*Algoriphagus*)或噬纤维菌属(*Cytophaga*)密切相关的基因，表明这些基因发生了基因转移[6]。Wang 等研究发现，在普通小球藻(*Chlorella vulgaris*)与液体猪粪中的细菌共培养时，共培养体系中生物量高于单独培养，在共培养结束时，沉淀 30 min 后共培养组有 95.5%的生物量沉降，而纯藻类组仅有 40.4%的生物量沉降[7]，说明该体系中细菌具有促进共培养生物量沉降的潜能。此外，微藻可以促使细菌分泌生长素类物质，淡水栅藻(*Scenedesmus* sp.) LX1 与细菌共培养时可促进细菌分泌生长素(indole-3-acetic acid, IAA)，进而促进微藻的生长以及生物质的积累[8]。需要注意的是，微藻与细菌共培养时藻菌很难完全分离，微藻生物质在提取时损失较大。因此，只有少数细菌具有与微藻发展共生关系的潜力。

### 1.2 微藻与真菌共培养

微藻与真菌共培养可以提高废水处理效率，Yang 等[9]用 *C. vulgaris* 与曲霉(*Aspergillus* sp.)共培养处理糖蜜废水，在真菌酶的作用下，糖蜜废水中的有机物转化成可溶性营养物质，供微藻吸收利用。共培养后废水中化学需氧量(chemical oxygen demand, COD)、总氮(total nitrogen, TN)和总磷(total phosphorus, TP)去除率分别为 70.68%、67.09%和 88.39%，$NH_3$-N 去除率提高至 94.72%[9]。此外，微藻与真菌菌丝通过电荷中和、疏水作用粘连在一起形成真菌-微藻颗粒，促进生物絮凝[10]。丝状真菌烟曲霉(*Aspergillus fumigatus*)分别与 11 种微藻共培养，24 h 后 *A. fumigatus* 与 *C. vulgaris*、亚头假藻(*P. subcapitata*)、四叶藻(*S. quadricauda*)都显示出高达 90%的絮凝率[11]。微藻与真菌共培养涉及到信号传导，其相互作用机制尚不明确，需要通过分子水平的研究进一步了解微生物之间的相互作用。微藻与真菌共培养时，很难建立无菌的微藻与真菌共培养系统，容易造成细菌的污染，在商业用途中效率低下。

### 1.3 微藻与微藻共培养

与前述两类共培养体系相比，微藻与微藻共培养(简称藻藻共培养)具有诸多优势。当微藻与细菌共培养时，细菌生长速度通常比微藻快，导致微藻细胞的生长处于劣势甚至死亡，而藻藻共培养中微藻细胞生长速度通常比较接近，更适合建立稳定的共培养体系；在微藻与真菌共培养体系中收获生物质时，微藻与真菌难以分离，加大生物质回收难度，而藻藻共培养产生的细胞外聚合物有助于细胞聚集，使自絮凝在培养液中形成，从而方便生物质回收，提供稳定的生物质组成，并可直接用于下游加工[12-13]。微藻间共培养可以通过群体感应等相互作用进行信息交流，提高抵御不良环境的能力。微藻通过细胞接触混合生长，彼此相互制约相互促进，形成一个稳定的混合体。功能互补的微藻可以通过共培养体系促进彼此营养物质的吸收，从而提高共培养的生物质生产率与脂质产量。

从共培养的原理上看，藻菌共培养与藻藻共培养都利用了微生物间的相互作用，藻菌共培养中微藻通过光合作用释放 $O_2$ 和有机物供需氧菌生长，细菌通过呼吸作用产生的有机物以及 $CO_2$ 可作为微藻光合作用原料，从而形成良性的物质循环；藻藻共培养中藻株间不仅通过营养交换作用相互促进生长，外界的培养条件变化也可能改变微藻产生小分子代谢物质的能力，并且微藻间分泌的植物激素在细胞间起主要作用。从培养过程来看，藻菌共培养在培养末期收获时藻菌难以分离，难以提取微藻生物

质，并且共培养期间菌类生长迅速，微藻常常无法获得生长所需要的光照以及营养物质而导致培养体系崩溃；藻藻共培养能够提高微藻生物质以及油脂产率，收获过程容易，但藻藻共培养容易积累胞外多糖阻碍营养物质的吸收，应谨慎选择共培养的供试藻株。

## 2 藻藻共培养对生物质以及油脂产率的影响

藻藻共培养时可以提高共培养系统中的生物质生产率。例如纤小裸藻(*Euglena gracilis*)和月牙藻(*Selenastrum* sp.)混合培养时，共培养的生物质生产率高于单一培养[14]。Rashid 等将 *Ettlia* sp. YC001 和小球藻(*Chlorella* sp.)共培养，在各接种比例下，共培养的生物质生产率均高于 *Ettlia* sp. YC001 单一培养；在 1:8 的接种比例下单一培养 *Ettlia* sp. YC001、*Chlorella* sp.的生物质分别是 0.26 g/L 和 0.44 g/L，共培养生物质最高至 0.74 g/L[15]。*Chlorella* sp. U4341 和单针藻(*Monoraphidium* sp.) FXY-10 共培养显著提高了生物质的积累和总脂产量，生物质生产率达到 62.00 mg/(L·d)，脂质产率为 29.52 mg/(L·d)，显著高于单培养[16]，表明藻藻共培养在提高生物质、油脂以及高效提取生物质方面具有潜力。

当两种微藻共培养比例不同时，脂质含量也发生变化，黄丝藻(*Tribonema* sp.)与 *Chlorella zofingiensis* 共培养时，接种比例为 3:7 与 1:1 的脂质含量分别占微藻干重的 43.24%、44.12%，单独培养 *C. zofingiensis* 时脂质含量仅为 18.82%[17]。*Scenedesmus* sp. LX1 与雨生红球藻(*Haematococcus pluvialis*)在 4:1、1:10 的比例下共培养 13 d，生物质与脂质含量比单一藻种显著提高，甘油三酯的含量分别达 6.9 mg/L、9.3 mg/L[18]。伪矮海链藻(*Thalassiosira pseudonana*)和球等鞭金藻(*Isochrysis galbana*)接种比例为 1:1 时共培养，生物质最高达到 1.45 g/L，当接种比例为 3:7 时脂质含量最高[19],说明优化藻细胞接种比例可进一步提升共培养体系产油脂效率。

## 3 藻藻共培养对生物质成分的影响

微藻可用于生产高价值的生物活性物质(图 1)，例如脂肪酸、维生素、蛋白质、色素以及胞外多糖 (extracellular polysaccharides, EPS)[20]。微藻是地球上主要的多不饱和脂肪酸(polyunsaturated fatty acid, PUFA)生产者。在代谢过程中可以合成二十碳五烯酸(eicosapentaenoic acid, EPA)、二十二碳六烯酸(docosahexaenoic acid, DHA)和花生四烯酸[21]。一些藻株可高效合成维生素，如维生素 A、B、D、K[22]。微藻中 *C. vulgaris*、盐藻(*Dunaliella salina*)、*H. pluvialis* 和斜生栅列藻(*Scenedesmus obliquus*)有较高的蛋白质含量[23]。微藻中还含有叶绿素以及其他与光合作用有关的色素，例如类胡萝卜素、虾青素[24]。Rashid 等研究发现，当 *Chlorella* sp. 与 *Ettlia* sp. YC001 共培养时，脂肪酸的含量显著高于单一培养 *Ettlia* sp. YC001 中脂肪酸的含量，蛋白质含量显著高于单一培养 *Chlorella* sp. 的蛋白质含量[15]。微拟球藻(*Nannochloropsis oculata*)和大溪地金藻(*Tisochrysis lutea*)在盐水培养基中共培养时，叶绿素和类胡萝卜素浓度均有所增加[25]。有些微藻物种共培养时因微藻生物质大量增加导致光合作用低下，色素产量降低，所以应选择合适的微藻物种进行共培养。此外，与 *Cyclotella cryptica* 单独培养相比，*C. cryptica* 和 *Skeletonema marinoi* 共培养提高了维生素 A、C、$B_1$、$B_{12}$、$B_6$和 E 的浓度，共培养时维生素含量增加了 10%以上[26]。

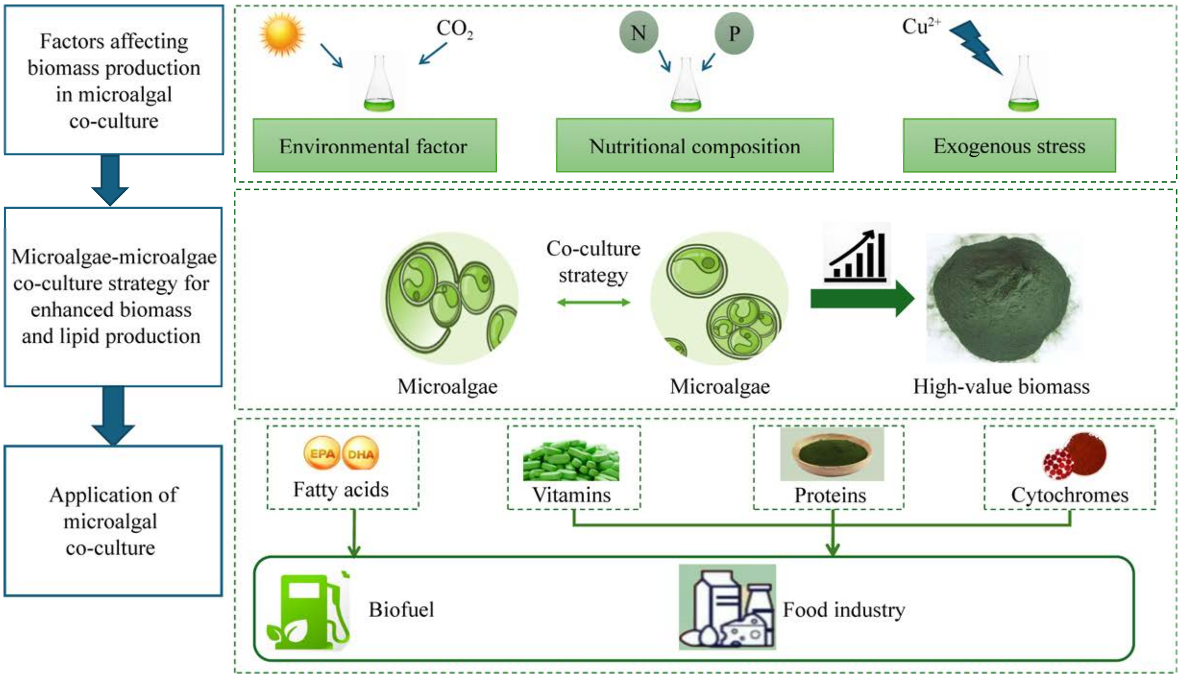

**图 1　藻藻共培养产生物质的影响因素、生物质成分及资源化应用**

Figure 1　Influencing factors, biomass composition and resource utilization of microalgal co-culture.

微藻生物质收获的方式有多种，其中生物絮凝能够避免微生物二次污染，降低收获成本，生物絮凝中 EPS 发挥重要作用。EPS 是微藻在生长代谢过程中分泌到细胞外的一类大分子多糖化合物，例如葡聚糖、半乳聚糖、阿拉伯木聚糖[27]。EPS 的存在让藻细胞之间相互吸附形成自絮凝，还能保护微藻免受外来微生物的污染[28]。当栅藻(*Desmodesmus* sp.) ZFY 和 *Monoraphidium* sp. QLY-1 共培养时，总 EPS 浓度为 368.40 mg/L，显著高于单一培养所产 EPS[29]。微藻培养过程产生的 EPS 有利于微藻生物质的收获，但过多的 EPS 会阻碍营养物质的吸收，因此藻藻共培养还应关注 EPS 产生动态。

# 4　藻藻共培养产生物质的影响因素

## 4.1　环境因素

微藻在进行光合作用时，所产生的生物质、脂质受到光照强度与 CO$_2$浓度的影响。当 *Scenedesmus* sp.、绿球藻(*Chlorococcum* sp.)、*Chlorella* sp.和三角褐指藻(*Phaeodactylum tricornutum*)混合培养，在光照强度为 116 μmol/(m$^2$·s)的条件下，混合培养所产生的生物质高于单一培养，适宜的光照强度具有提升生物质的潜能[30]。当 *Chlorella* sp.与废水野生藻类共培养时，在 CO$_2$浓度 3.4%、光照强度 180 μmol/(m$^2$·s)条件下，最大干生物质生产率达到 9.9 g/L，在 CO$_2$浓度 2.2%、光照强度 187 μmol/(m$^2$·s)的条件下，干生物质生产率低于 9.9 g/L，最大细胞数达到 8.4×10$^8$ 细胞/mL[31]。

## 4.2　营养成分

微藻生物质生产率与培养基的营养成分密切相关。当 *C. vulgaris* 与二形栅藻(*Scenedesmus dimorphus*)利用硝酸盐、铵、尿素 3 种氮源混合培养时，其生物质生产率为 352.30 mg/(L·d)，显著高于单一氮源[32]。铜绿微囊藻(*Microcystis aeruginosa*)与蛋白核小球藻(*Chlorella pyrenoidosa*)分别在

溶解无机磷、磷酸单酯葡萄糖-6-磷酸酯和磷酸β-甘油酯 3 种磷底物中共培养后，共培养中的 *C. pyrenoidosa* 细胞密度在 3 种磷底物下分别达到 $9.84\times10^6$ 细胞/mL、$9.33\times10^6$ 细胞/mL、$7.32\times10^6$ 细胞/mL[33]。在 3 种磷底物中无机磷为首选的磷源，该共培养体系在不同的磷条件下能够自我调节对磷的吸收能力，合适的磷源能够促进微藻生物质的增加。

### 4.3 外源物质胁迫

与单一培养相比，微藻间共培养可更好地应对不利环境条件[18]。Zhang 等[34]比较了 *Chlorella regularis* 和斜生栅藻(*S. obliquus*)在群体感应信号分子 $C_6$-HSL 的胁迫下，单培养和共培养的细胞生长和脂质生成情况(表 1)[34]。当 *C. regularis* 与 *S. obliquus* 单独暴露在 $C_6$-HSL 的环境胁迫下，会影响抗氧化酶和线粒体活性，使得微藻生长受到显著抑制，而共培养条件下 $C_6$-HSL 对藻细胞的生长抑制减弱，共培养体系的产脂率比 *C. regularis* 和 *S. obliquus* 单培养的产脂率高 20%−79%[34]。*Chlorella sorokiniana* 与 *Kirchneriella obesa* 共培养时，在 $2\times10^{-7}$ mol/L $Cu^{2+}$浓度下，共培养的细胞生长速率高于在相同 $Cu^{2+}$浓度下单一培养物的生长速率[35]。说明藻藻共培养具有抵御环境胁迫的潜能。

## 5 藻藻共培养资源化应用

### 5.1 生物燃料

微藻生物质中的脂质是生物燃料的良好原料。如表 1 所示，*C. regularis* 和 *S. obliquus* 共培养可以积累较多的生物质，获得的脂肪酸成分由 $C_{16}$–$C_{18}$ 脂肪酸组成，适用于生物柴油的生产[34]。将微藻与废水处理相结合时，微藻产油的同时处理废水中营养物质[36]。本课题组 Wang 等研究发现，*C. sorokiniana* HDMA-16 在亚麻废水中生长时，生物质和脂质产量达到 785.7 mg/L、151.5 RFU/(L·d)，废水中 $NH_4^+$-N、

**表 1 藻-藻共培养产生物质及脂质的研究归纳**

Table 1 Research induction of biomass production and lipid production by co-culture of microalgal

| Co-culture | | Ratio | Media | *T*/°C | Biomass productivity (mg/(L·d)) | Lipid content (%) | Lipid productivity (mg/(L·d)) | References |
|---|---|---|---|---|---|---|---|---|
| Microalgae 1 | Microalgae 2 | | | | | | | |
| *Chlorella* sp. | *Ettlia* sp. YC001 | 1:8 | BG11 | 25±2 | 740.000 | 11.00 | 180.8 | [15] |
| *Chlorella* sp. U4341 | *Monoraphidium* sp. FXY-10 | − | BBM | 25±1 | 62.000 | 47.79 | 29.52 | [16] |
| *C. zofingiensis* | *Tribonema* sp. | 1:1 | Swine wastewater diluted with fishery wastewater | − | 0.195 | 44.12 | − | [17] |
| *Desmodesmus* sp. ZFY | *Monoraphidium* sp. QLY-1 | − | Modified BG11 | 25±1 | − | − | 93.99 | [29] |
| *C. vulgaris* | *S. dimorphus* | − | Modified Bristol medium | 23 | 300.000−350.000 | 21.00−24.00 | 70.00−84.00 | [32] |
| *C. regularis* | *S. obliquus* | − | Modified BG11 | 25±1 | − | − | 120.00 | [34] |

−: No relevant information found in literature.

TP、COD去除率可达26.86%、99.59%和29.39%[37]。说明 *C. sorokiniana* HDMA-16 具有利用废水产油的同时处理废水的潜能。当 *C. vulgaris* 与 *S. dimorphus* 在稀释度 10%垃圾渗滤液中共培养，生物质在 10 d 内达到 0.266 g/L，产脂量在 10 d 内达到 49.83 mg/L，$C_{16}$–$C_{18}$脂肪酸含量达到 88.81%[38]。*C. zofingiensis* 与 *Scenedesmus* sp.在乳品废水中共培养时，第 2 天即可实现 62.87%的 COD 去除率，最大脂质生产率为 150.6 mg/(L·d)，所产脂肪酸以棕榈酸、硬脂酸、油酸、亚油酸和亚麻酸为主，适合用于生物柴油的生产，提高藻类生物柴油的燃料性能[39]。藻藻共培养能够有效去除废水中的营养物质并提高共培养脂质含量，是有经济效益的生物燃料的生产方法。

### 5.2 食品工业

一些藻类富含蛋白质、PUFA 和维生素，具有较高的营养价值[40]。例如，螺旋藻富含的维生素 $B_1$、维生素 $B_2$ 等能够用于食品产业[41]。微藻蛋白具有完整的必需氨基酸谱，可以用于水产养殖，促进鱼类生长代谢[42]。如图 1 所示，富含油脂的微藻生物质可被用作食品添加剂，其中的 PUFA 含量与鱼油相当[43]。当 *Scenedesmus* sp. DDVG I 与 *Limnothrix* sp. DDVG II 在生活废水中共培养(表 2)，其必需氨基酸的含量与大豆、螺旋藻氨基酸含量相当[44]。在 *E. gracilis* 与 *Selenastrum* sp.共培养时，PUFA 比 *E. gracilis* 单一培养 PUFA 产量高，尤其是 EPA 和 DHA 的产量[14]。*T. lutea* 和 *Microchloropsis salina* 在共培养 8 d 后，生物质增加的同时 DHA 含量提高了 33%[45]。

## 6 展望

微藻共培养体系与单一培养相比呈现出较高的稳定性，有潜力提高微藻的生物质以及油脂产量。然而，目前微藻共培养仍然停留在实

**表 2 藻藻共培养类群及应用**

Table 2 Species and applications by co-culture of microalgal

| Co-culture species | | Application | References |
|---|---|---|---|
| Group | Algal species | | |
| *Chlorophyta* | *Chlorella* sp. | Improving biomass productivity and biodiesel production | [15] |
| *Chlorophyta* | *Ettlia* sp. YC001 | | |
| | *Chlorella* sp. U4341 | Enhancing lipid productivity | [16] |
| | *Monoraphidium* sp. FXY-10 | | |
| | *Scenedesmus* sp. LX1 | Enhancing microalgal biomass and triacylglycerol production | [18] |
| | *H. pluvialis* | | |
| | *Desmodesmus* sp. ZFY | An effective method for harvesting of microalga: coculture-induced self-flocculation | [29] |
| | *Monoraphidium* sp. QLY-1 | | |
| *Chlorophyta* | *Selenastrum* sp. | Conversion of biowaste leachate to valuable biomass | [14] |
| *Euglena* | *E. gracilis* | | |
| *Chlorophyta* | *C. zofingiensis* | Treating swine wastewater diluted with fishery wastewater to facilitate harvest | [17] |
| *Xanthophyta* | *Tribonema* sp. | | |
| *Bacillariophyta* | *T. pseudonana* | Treatment of fishery wastewater | [19] |
| *Chrysophyta* | *I. galbana* | | |
| *Chlorophyta* | *N. oculata* | Obtaining valuable compounds | [25] |
| *Haptophyta* | *T. lutea* | | |
| *Bacillariophyta* | *C. cryptica* | Enhancing vitamin and bioactive compounds production | [26] |
| *Bacillariophyta* | *S. marinoi* | | |
| *Chlorophyta* | *Scenedesmus* sp. DDVG I | Bioremediation of domestic wastewater | [44] |
| *Cyanophyta* | *Limnothrix* sp. DDVG II | | |

验室阶段，技术尚不成熟。有些藻种在共培养时相互竞争，导致不饱和脂肪酸、色素、蛋白质和维生素产量降低，应谨慎选择共培养物种。未来可通过基因工程方法进一步改进微藻产油潜能，促进藻藻共培养体系在碳减排领域的应用。同时可利用组学进一步了解藻藻共培养相互作用机制，深入挖掘藻藻共培养在污水处理、土壤修复方面的应用潜能，促进藻藻共培养所产生物质在生物燃料、生物肥、食品保健、动物饲料方面的资源化应用。

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